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DEVELOPMENT OF AN INTEGRATED AEROELASTIC MULTIBODY MORPHING SIMULATION TOOL (POSTPRINT)

Gregory W. Reich, Jason C. Bowman, Brian Sanders, and Geoffrey J. Frank

Advanced Structural Concepts Branch
Structures Division

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14. ABSTRACT
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Development of an Integrated Aeroelastic Multibody Morphing Simulation Tool

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This paper describes the development of a tool for simulating the flight of a morphing aircraft during the morphing process. Also discussed are current-generation tools for modeling vehicle flight and illustrations of how these tools are as yet too immature for modeling of the flight of an aircraft during morphing of the wings. A framework is developed for modeling vehicle flight that incorporates vehicle morphing. The procedures outlined in the paper are sufficiently general to accommodate aircraft utilizing changes in sweep, span, or area. The current state of the art and the planned developments are illustrated through their application to the flight of a folding-wing vehicle.

Nomenclature

F_M	=	total modal load vector
$\mathbf{q}$	=	vector of ADAMS degrees of freedom
t	=	time
s	=	modal force weighting function
g	=	individual modal force weights
F	=	constant modal load
Φ	=	matrix of Craig-Bampton component modes
q_∞	=	freestream dynamic pressure
α	=	angle of attack
δ	=	vector of control surface deflections

I. Introduction

Much has been said recently about the potential capability increase of a morphing aircraft as compared to a fixed-wing vehicle. Clearly, there are a number of potential benefits to be gained based on the expansion of a vehicle's flight envelope, making this an attractive goal for aircraft designers. The broad goals of significant increase in span, chord, and wing area represent a massive challenge for designers to realize systems that can achieve these goals while simultaneously maintaining the basic integrity of the vehicle system itself. Research in this area, while experiencing rapid growth and some impressive early successes, is still in its infancy, and there remain a number of critical areas that represent virgin territory for researchers and must be addressed before a morphing vehicle can become a reality.

One research area that has not yet been explored is the simulation of these vehicles in flight. Steady-state analysis at multiple morphing states may not be adequate to understand the system behavior. Simulation of the system allows the designer to examine the interplay between the shape change, aerodynamics, control, structural

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dynamics, actuation, and other disciplines in a time-dependent manner. Additionally, a simulation environment allows the designer to test different morphing mechanisms and system designs before any physical hardware is built.

From a stability and control perspective, the basic stability of the vehicle can be examined by traditional methods for particular configurations, but the stability during the morphing process itself is unknown. Stability and control of shape-changing structures involves not only the stability and control of the vehicle but also that of the mechanism. For single degree-of-freedom systems, this is a relatively simple problem. For multi degree-of-freedom systems, however, there are an infinite number of paths from one shape to another. This path is not only determined by the stability and control of the vehicle through the shape change, but also by preferred paths of the mechanism that may come about due to mechanism instabilities or actuation force and energy considerations. Finally, time-varying flight control schemes for control of the vehicle during morphing can be investigated in a truly transient dynamic simulation.

From an aerodynamic viewpoint, there are several effects that can have a profound impact on the load predictions for a morphing vehicle. The need for unsteady effects in the computation of loads depends on the time and length scales at which the morphing, vehicle maneuvers, and transient structural dynamics occur. The dynamic aeroelastic behavior of the vehicle may not be a critical aspect to capture in the simulation, but the unsteadiness in wakes and boundary conditions may be important if the morphing action is fast enough. A comparison of responses incorporating different aerodynamic effects can highlight the important unsteadiness as well as the terms that have minimal effect on the overall system behavior. Additionally, depending on the type of morphing that occurs, there may be interaction effects between components. For instance, in a folding-wing vehicle, as the wing folds the inner wing may actually fold into or along the side of the fuselage. The aerodynamic loads on those parts as they converge may be critical to capture for proper load prediction.

Structurally, the interaction between flexible bodies and kinematic mechanisms is extremely important for morphing performance, especially for morphing systems that accomplish shape change through in-plane deformation of the wing. Aeroelastic wing deformation can cause binding and locking of a mechanism, which can be analyzed in a simulation environment. Incorporation of the aerodynamics into a multibody analysis tool allows the designer to compute complex aerodynamic loads that are highly dependent on the position of the mechanism. The incorporation of actuator dynamics also increases the accuracy of the structural response by inclusion of the stiffness and damping inherent in the actuation system.

What is the current state of the art in the analysis and simulation flexible multibody dynamics with aerodynamic loading? Clearly, there are a number of codes that do individual aspects of this problem very well. Multibody dynamics codes such as ADAMS and DYMORE can be used to model rigid or flexible bodies under various loading conditions, but lack the fidelity of aerodynamic analysis required for complex distributed time-varying loads. The current generation of structural design tools used for aeroelastic loads analysis (such as NASTRAN, ASTROS, etc) was developed for static or dynamic analysis of time-invariant structures, and therefore by definition cannot be used to analyze morphing structures in a time-varying manner. These tools can also analyze the structural response of an aircraft in simple maneuvers, but do not include any control capability beyond perhaps a trim optimization procedure to find a trim point for a given maneuver.

Clearly, then, there is a need for a tool that allows the engineer to simulate the performance of a morphing vehicle in a time-dependent manner during a morphing maneuver. At a minimum, the tool should incorporate aerodynamics with time-varying, flexible wakes, flexible and rigid-body motion of the structure, and a flight control system capable of creating morphing maneuvers and providing vehicle stability during flight.

The remainder of the paper is divided into two parts: the first part describes in more detail the current capabilities of an interaction between NASTRAN and ADAMS. The second part describes the development and capabilities of a new tool based on ADAMS, NASTRAN, a vortex-lattice aerodynamic code, and Matlab that is an improvement on the first, and enables a designer to analyze and simulate a time-varying, flexible, multibody, flying morphing vehicle. Both parts will contain examples that highlight the capabilities and limitations of each. A time-scale analysis, while beyond the scope of the present paper, is also in the works to understand the interaction between aerodynamics, vehicle and mechanism kinematics, and structural flexibility at different time scales.

II. Current Capabilities

With the recent acquisition of Mechanical Dynamics by MSC.Software, it should soon be possible to tightly integrate the capabilities of NASTRAN and ADAMS. This means that advanced finite element models can be combined with multi-body dynamics models to simulate complex flexible multi-body systems. The aerodynamic panel methods incorporated into NASTRAN produce good first-order steady aerodynamic loads. ADAMS currently allows incorporation of flexible bodies from finite element analyses through a Craig-Bampton component mode synthesis[1] process. Distributed loads for flexible bodies can also be imported to ADAMS via a modal load definition, which allows for aerodynamic loads to be incorporated in certain limited cases.

The application of modal loads onto flexible bodies in ADAMS is based on the following representation[2]:

$$F_M(\mathbf{q},t) = s(\mathbf{q},t)\left[g_1(t)F_1 + \ldots + g_n(t)F_n\right] \tag{1}$$

where $\mathbf{q}$ is the vector of rigid-body and flexible degrees of freedom, s is a time- and state-dependent scaling function, g_i are time-dependent scaling functions for different load vectors, and $F_i = \Phi^T F_{aero}$ are constant modal load vectors. Consider a non-morphing vehicle for which we wish to simulate a simple symmetric maneuver. From NASTRAN, the vehicle finite element model can be imported to ADAMS. The baseline aerodynamic loads at a given trim state can also be imported, along with load sensitivities due to angle of attack or control surface deflections. Then, in ADAMS, the total aerodynamic loads could be written as

$$F_M(\mathbf{q},t) = q_\infty\left[F_{baseline} + \alpha(t)\frac{\partial F}{\partial \alpha} + \delta(t)^T\frac{\partial F}{\partial \delta}\right] \tag{2}$$

where α is a known function of angle of attack in time and δ is a vector of known control surface deflections, also as a function of time. This can be implemented in the manner of Eq. (1), and a full-vehicle simulation can be computed in ADAMS. A control system can also be incorporated into a simulation in order to command the trim parameters. Note that compressibility effects are not considered here, but could also be added to Eq. (2). As long as the vehicle does not violate any of the basic assumptions that result from the importation of the aerodynamic loads, then the modal loads applied to the vehicle should be accurate (at least to the level of accuracy of the original loads computation).

Simulations of this type have been demonstrated by McConville *et al*[3]. They simulated a vehicle performing a "lob" maneuver, which is a climb and simultaneous stores release. The vehicle was modeled as a single flexible body imported from NASTRAN, while the store was a separate aerodynamic body. Baseline aerodynamic data for a given trim condition was imported as a modal force into ADAMS. Aerodynamic load sensitivities with respect to control surface deflections were also imported. The maneuver was then created in ADAMS by creating functions of control deflections, velocity, and other vehicle state information to control the aircraft trajectory.

As another example, consider the vehicle shown in Figure 1. It is a symmetric, free-flying version of a Lockheed-Martin morphing wind tunnel model[4] in the unfolded configuration. The finite element model has been imported from NASTRAN into ADAMS as a single flexible body. Steady aerodynamic loads are computed for the basic vehicle, and sensitivities are included for control surface deflections and angle of attack. These loads are imported into ADAMS as modal loads, which mean that the physical loads and load increments have been pre-multiplied by the Craig-Bampton component modes related to the flexible body. Vehicle simulation is then achieved by computing aerodynamic loads from the combination of trim parameters and dynamic pressure, which are pre-defined.

Now consider the case of a morphing vehicle, one in which the basic vehicle geometry can change with time. Clearly, in Eq. (1), the load vectors themselves cannot change as a function of configuration, but load sensitivities to the trim parameters are dependent on the vehicle shape. Therefore, Eqs. (1) and (2) are not sufficient to model the aerodynamic loads for a shape-changing vehicle. Some other sort of interpolation must be done in order to correctly model the loads in this situation. The most recent release of ADAMS (2005 r2) has added the flexibility of a time-

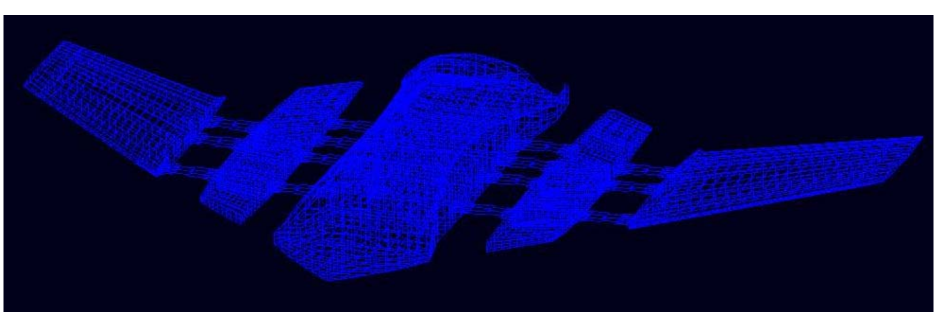

Figure 1: Free-flying model as a single flexible body.

and state-dependent modal force vector[2]:

$$F_M(\mathbf{q},t) = F(\mathbf{q},t) \tag{3}$$

This is an improvement over Eq. (1), as modal loads can be determined based on the current state (**q**). However, this paradigm of pre-computing loads and then interpolating between a limited set of known loads can be prohibitively expensive. It means that, to simulate a morphing vehicle, the aerodynamic loads and control sensitivities must be computed for a number of different full-vehicle models in different stages of the morphing process. Then, the simulation must interpolate the loads at any given configuration from this predetermined set of loads. Note that as the number of degrees of freedom in the morphing mechanism increases, the number of required predetermined load cases goes up exponentially. For a folding-wing type of morphing vehicle, this means computing aerodynamic loads at a range of fold angles. For an in-plane morphing vehicle with two or more degrees of freedom, the number of load cases would be significantly higher.

III. Integrated Aeroelastic Multi-body Morphing Simulation

So what is different with an integrated simulation tool? The big difference comes in the computation and application of the aerodynamics loads. Rather than pre-computing a set of steady loads and sensitivities, transforming them into equivalent modal loads, and then interpolating for shapes in between computed configurations, the aerodynamic loads are directly computed at each time step for the current morphing shape. The spline or interpolation between the aerodynamic grid and the structural model is also re-computed at each time step. Depending on the complexity of the aerodynamic code, time-dependent effects such as moving wakes, velocity boundary conditions, and unsteady aerodynamic terms can also be incorporated into the analysis.

The tool that has been developed is called IAMMS: Integrated Aeroelastic Multi-body Morphing Simulation. The tool is based around the ADAMS multibody dynamics code, which is utilized to perform time integration of the equations of motion for the multi-body representation of the morphing aircraft. Loading is computed at each time step by an AFRL-developed code, which uses a vortex lattice method for computation of the aerodynamic loads and splining techniques to interpolate the aerodynamic forces onto the structure. An automatic flight control system is included using a Matlab/SIMULINK-based multi-loop feedback control system developed by AFRL. The inner control loop uses dynamic inversion, while the outer loop includes standard Proportional-Integral-Derivative (PID) controllers.

For IAMMS, models are typically created in ADAMS via the flexible body interface with NASTRAN. Each component must be created separately so that ADAMS can treat them as separate parts. If the entire vehicle is read in as a single flexible body, then no rigid-body motion can occur between components that are included in the flexible body. Consider the vehicle in Figure 2. It is slightly different version of the same free-flying MAS wind tunnel model from Lockheed. In Figure 2, each of the major components, the outer wings, inner wings, and the fuselage, are all shown in different colors to indicate that they are separate bodies, rather than all in the same color as in Figure 1 where the entire vehicle was represented by a single flexible body.

The flexible bodies are connected in ADAMS by joints. The complex drive and actuation system used on the wind tunnel model has been simplified for this simulation, while retaining the key effect of joint flexibility. Figure 3 shows a close-up of one of the joints along the outer right hingeline. The joint consists of three small disks. Two of the disks are rigidly attached to the flexible bodies, one on each side (indicated by the lock icons). The third disk is

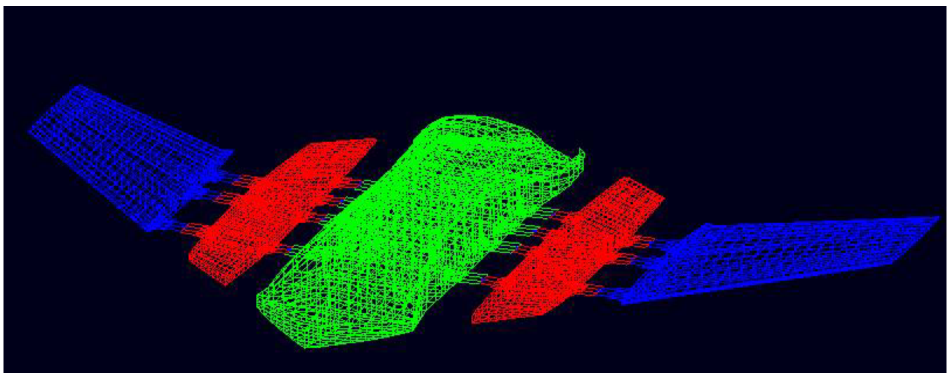

Figure 2: Free-flying model as separate bodies.

attached to each of the other two with revolute joints. One joint includes a torsional spring (the yellow arrow icon) to model the flexibility of the actuation system, and the motion of the other joint is commanded as the wing fold position command produced by the control system (the white arrow icon).

Note that there are multiple hinge attachment locations on each fold line. For rigid bodies, these represent redundant constraints. For flexible bodies, multiple attachments are permissible because the flexibility in the bodies allows for numerical noise and misalignment in the joints. As the loads change during the morphing process, one can see the load paths change by looking at the relative hinge moments across each hinge. See the companion paper by Scarlett[5] for more information on this phenomenon.

Aerodynamic loads are created on this model via an in-house vortex lattice code called JAC. The aerodynamic panel model, such as the unfolded configuration shown in Figure 4, is created at each time step based on the current position of the wing components. A splining process, very similar to the methods implemented in NASTRAN[6] and ASTROS[7], is utilized to determine the shape of the panel model based on the motion of the joints and the flexibility of the structure. The current vehicle state (position, orientation, and rates) is also fed to the aerodynamic code, which returns loads at the center of each aero panel. The splining routine then transfers the aerodynamic panel loads to a set of structural load points on each body.

Note that the panel model in Figure 4 includes a horizontal tail that does not appear on the wind tunnel model. This fictional surface, as well as a fictional rudder, has been added in order to control the lateral/directional behavior of the vehicle. Additionally, fictional trailing-edge control surfaces have been added to the outer wings to provide longitudinal stability. The wind tunnel model was not designed with any of these surfaces, and they are not precise representations of the control surfaces that a vehicle of this sort would actually use. They are simply convenient

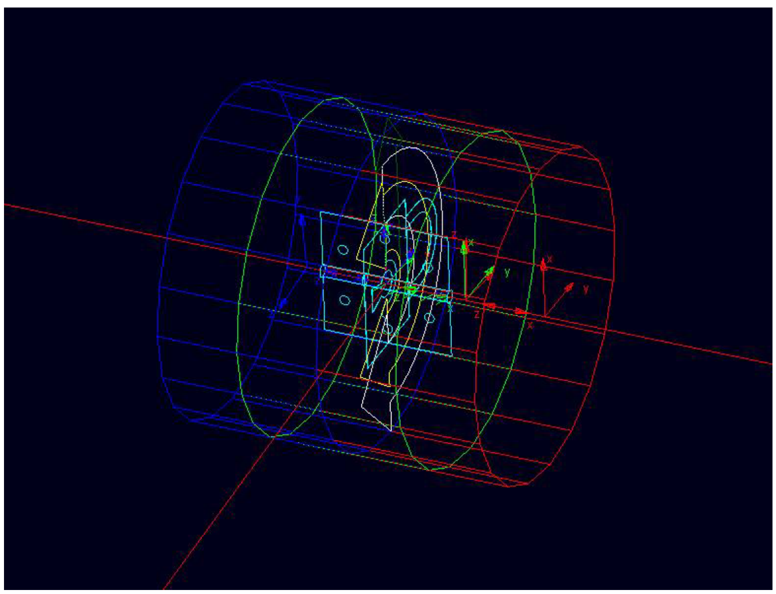

Figure 3: Close-up of a joint.

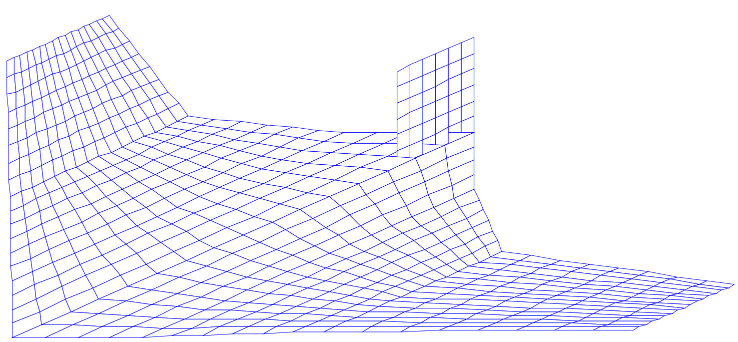

Figure 4: Aerodynamic panel model of the folding wing vehicle.

surfaces to have for stability and control of the free-flying vehicle. In addition to the fictional control surfaces, an applied thrust vector has been added as an additional control parameter. The excess thrust is computed in the control routine as a commanded thrust from an engine model minus a drag estimate and is input to the vehicle as a control input force.

To control the vehicle, a flight control system in Matlab/SIMULINK was linked to the ADAMS model. To provide this control system with the correct plant information, a number of measures and state variables were created in the ADAMS model. These measures included the vehicle state (position, orientation, and rates) as well as the current morphing configuration. ADAMS provides for an interface to SIMULINK via a "control system export" which creates a model for insertion into the control system diagram. This plant model, when called in SIMULINK, spawns an ADAMS/Solver process which loads the model and simulates the plant dynamics based on the control system inputs (thrust, control surface deflections, and morphing parameters).

The control system itself is a multi-loop vehicle stability and control scheme. The inner loop, which controls vehicle angular rates (pitch, roll, and yaw) is based on a dynamic inversion process[8]. This takes a model of the plant (in this case a stability and control model, interpolated from a suite of pre-determined morphing parameter models), inverts it, and then assigns closed-loop poles to meet some performance objective. The outer loop controls heading, altitude, speed, and other performance objectives directly through classical PID controls.

The simulation process, represented in Figure 5, actually is driven by the control system in SIMULINK. The performance objectives, including morphing profile, are set here, along with the total simulation time, control system time step, and plant/feedback communication interval. On initialization, the simulation spawns the ADAMS/Solver process, and the two processes run side-by-side. They are separate processes, can have separate integration time steps, and only swap input/output data at specific time intervals (the communication interval). This is called a "co-simulation", and while it is not the only method to integrate the ADAMS and SIMULINK processes, it is a very convenient and straightforward method to do so.

The ADAMS simulation itself is run based on settings in ADAMS/Solver. These settings control the type of numerical integration scheme used, the accuracy of the predictor/corrector and convergence of the various iterative steps in the process, etc. The solver also internally controls the step size for integration, as this is independent of the step size used by SIMULINK. In each time step, the solver collects all of the loads applied to the system. In order to compute the aerodynamic loads, the subroutine at the heart of IAMMS first queries the model for the vehicle state from the previous time step. This information (position, velocity, orientation, morphing positions and velocities with respect to the center of mass (CG), deformation of the flexible bodies, etc) is used to compute the aerodynamic panel model for the current time step. The aerodynamic code JAC then computes the aerodynamic forces on the vehicle, which are splined back to the structural components.

There are a few limitations to this simulation process. First, in the area of structural representation, the joint model does not accurately represent the actuation drive system for the wing fold. A simple torsional spring stiffness and damping is used to represent the potential flexibility in this system, but nothing is done to represent limitations in actuation force or power output. Second, in the area of aerodynamic force computation, the aerodynamic code is based on potential theory and cannot produce drag forces. A simple drag estimate is used in the control system in conjunction with the engine model to estimate the excess thrust that is applied to the aircraft, but this is applied to the vehicle center of gravity and no skin friction drag forces are applied to the surface of the wings. Finally, the aerodynamic loads that are computed for the vehicle are based on flat-plate aerodynamics, and no thickness or camber effects are included. These have small impact on the vehicle at small fold angles. However, at fold angles

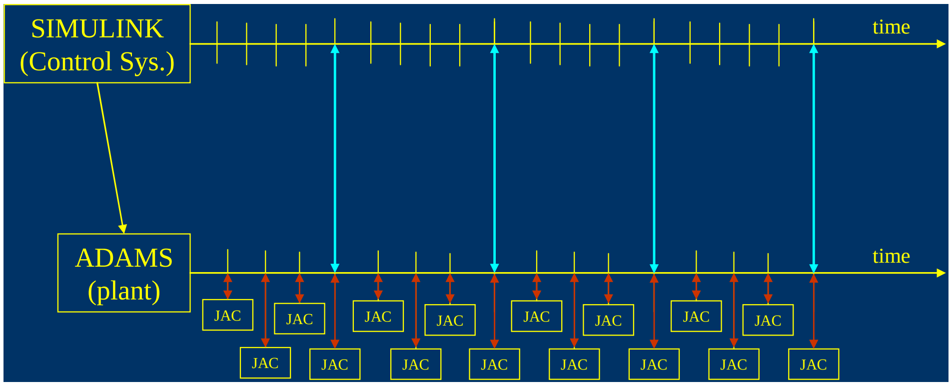

Figure 5: Co-simulation procedure for IAMMS.

approaching and above 90 degrees, the interaction effects between the inner and outer wings, and the inner wings and fuselage become quite important. More accurate aerodynamic codes need to be utilized to properly characterize the loads in these configurations. However, for the purposes of this simulation, the loads computed are adequate.

IV. Results

To demonstrate the utility of the IAMMS process, simple simulations of the model shown in Figure 2 have been computed. A level-flight scenario, a climb to altitude, a heading change, and a morph while maintaining altitude all demonstrate the capabilities of the simulation. The simulation results are best observed as time-doamin movies, which obviously cannot be included in printed paper. However, it is possible to show some of the outputs and states as related to the commands, which are presented below.

Figure 6 shows the simulation results for level flight (commanded 10,000 ft altitude, constant speed). The simulation starts just slightly above 10,000 ft, but not quite at equilibrium. During the first two seconds, the vehicle drops about 9 feet, and the control surfaces and angle of attack adjust in order to recover the altitude loss. After about 2 seconds, the model is in equilibrium and regaining altitude. From this time on, the vehicle maintains heading, speed, and altitude. In Figure 6 a number of different parameters are plotted. In the upper left of Figure 6, a snapshot of the vehicle is shown during the animation of the simulation results. The white line is a trace of the vehicle center of gravity (CG) during the simulation. At the upper right, the vehicle altitude is shown. The altitude command is 10,000 ft, and while the initial condition is just under 10,008 ft, the correct altitude is quickly recovered with overshoot of only about 1 ft. Other parameters shown in the figure include the angle of attack, control surface deflection, vehicle pitch rate about the CG, and the vehicle's speed, which increases from the commanded initial 650 ft/sec as the vehicle descends, and then recovers to the commanded rate after a few seconds.

A more interesting simulation is a simple morphing simulation. The same simulation as shown in Figure 6 is repeated, except that at 2 seconds, a wing fold command of 4 deg/sec is initiated. These results appear in Figure 7. In this figure, the model is shown at an intermediate time step of 9.94 sec, where the wings are folded at approximately 32 deg. Also shown in the figure are angle of attack, control surface deflection, speed, and wing fold angle, all as functions of time. What is interesting about this figure is the behavior of the model after the fold initiates at 2.0 sec. At 2.5 sec, a rather large spike in angle of attack and control surface deflections are seen. The source of this spike is not completely understood, but appears to be an artifact of the control system reacting to the startup acceleration of the wing fold. Because of this behavior, the altitude increases back up to 10,006 ft, which may seem like a large increase in the figure, but in reality is only a 0.06% increase in altitude.

At about the 4.0 sec point, the vehicle has regained its commanded speed, and the control system now attempts to bring the model back to the commanded altitude while continuing the folding action. What is interesting here is that the control surface deflections are decreasing, while the angle of attack increases. The control surfaces are not needed as they provide a nose-down pitching moment that is undesirable – the model is in trim at this point. The angle of attack increases in order to offset the reduction in lifting area of the wings caused by the folding action. This is more clearly seen in Figure 8, which shows the angle of attack plotted against the wing fold angle. After the angle of attack transients clear out, around the 5.0 sec mark, the angle of attack is nearly linear with respect to wing

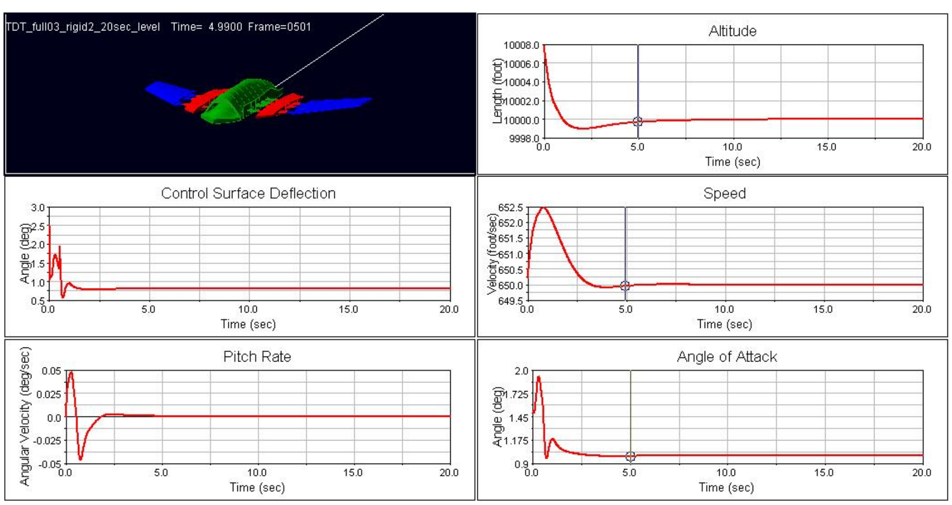

Figure 6: Results from a simple level-flight simulation.

fold angle. Another interesting phenomenon in Figure 7 is the small blips observed in control surface deflection and angle of attack between 15.0 and 18.0 sec. These small spikes are due to the mechanism binding up. The alignment of the different parts in the model is not numerically perfect – there are small numerical misalignments that cause the parts to move imperfectly with respect to one another.

Other simulations completed with this same model have similar results. Figure 9 shows a climb from 10,000 to 11,000 ft. Figure 10 demonstrates a 5 degree heading change at constant altitude and constant zero wing fold angle. These simulations demonstrate the ability of the flight control system to control the vehicle during flight.

V. Conclusion

A tool for free-flying simulation of a morphing vehicle has been developed. The tool combines a multibody dynamic simulation package with an aerodynamic code for load computation and a Matlab-based flight control system. Key features of the tool include the ability to model both non-linear large rigid-body motions and linear flexible-body deformations, and the integration of an aerodynamics package that allows for complete aerodynamic loads to be computed based on the current configuration at each integration step. The tool is used to simulate the flight of a simple folding wing vehicle concept, which demonstrates several performance phenomena of this type of vehicle.

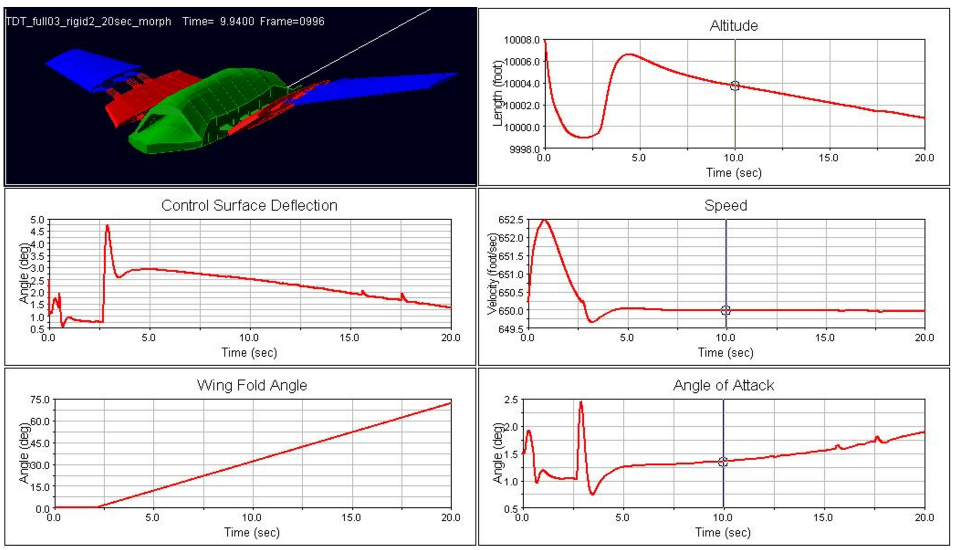

Figure 7: Result from level-flight morphing simulation.

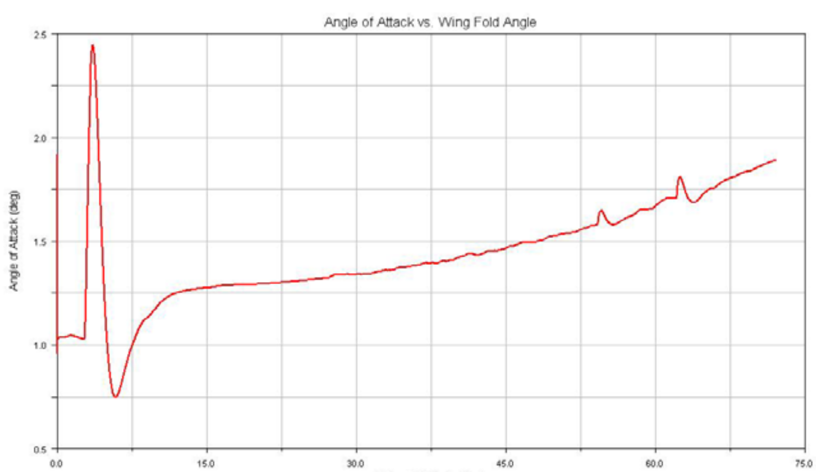

Figure 8: Angle of attack plotted against fold angle for the morphing simulation.

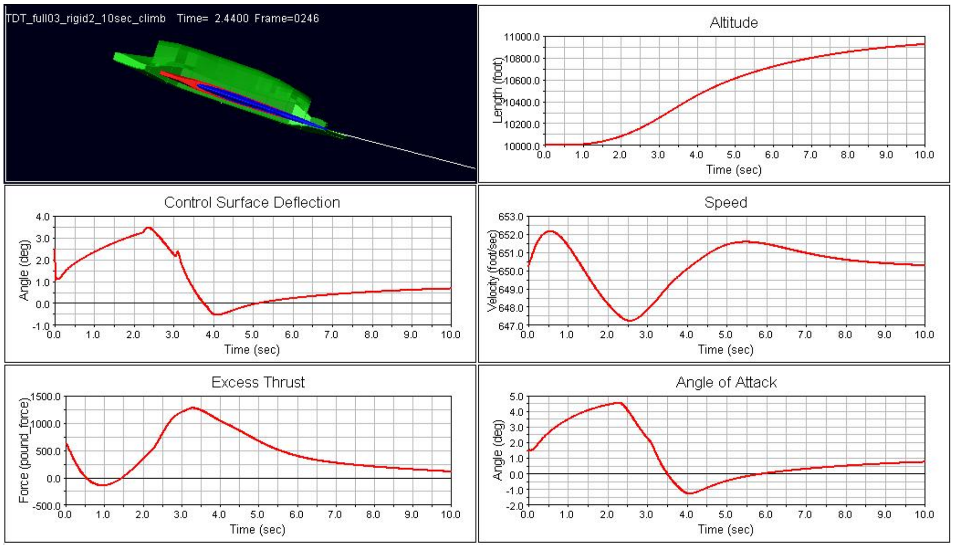

Figure 9: Results of a simple climb maneuver.

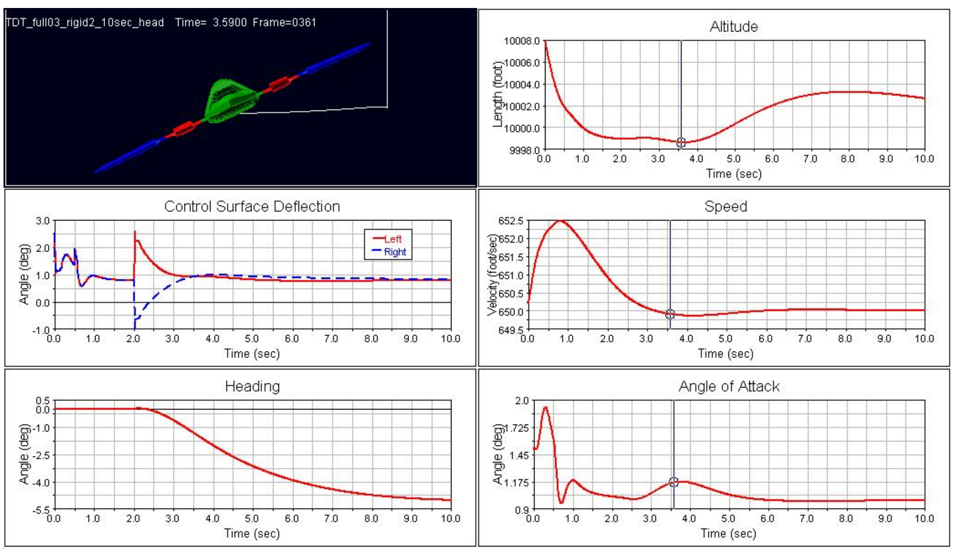

Figure 10: Results of a simple heading change.

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